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Proposal for the EIC Detector R&D program

Precision Timing Silicon Detectors for a Combined PID and Tracking System at EIC

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Abstract

We propose an R&D program to establish the applicability of ultra fast silicon sensor technology for constructing a combined time-of-flight (TOF) PID and tracking system at EIC detectors. The low gain avalanche diodes (LGAD) silicon sensors offer an excellent time resolution, and are being used by CMS and ATLAS experiments to build a new high precision timing layer at the high-luminosity (HL) LHC. Proponents have a strong involvement in the R&D and construction of the CMS MIP timing detector (MTD), particularly playing an instrumental role in pushing new PID capabilities with the MTD in the heavy-ion physics program. By leveraging experience at CMS, we propose an R&D program to optimize the timing and position resolution of LGADs sensors to meet the requirements of a compact TOF-tracker system at EIC. We first propose to systematically study the performance of much thinner LGADs to identify optimal sensor thickness and gain values that provide best time resolution (20 ps or better) for PID at EIC. Furthermore, we will perform detailed simulations to determine the position resolution of LGADs required for a tracking system, and investigate the feasibility of utilizing ultra-thin trench-isolated (TI) LGADs and AC-coupled LGADs to realize the proposed TOF-tracker system.

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1 Scientific Motivations

A high-energy high luminosity polarized electron-ion collider (EIC) will be constructed at Brookhaven National Laboratory (BNL) in the coming decade, as recently announced by the US Department of Energy. Its planned completion in 2030 will mark the start of the next new frontier of nuclear physics in which it will address many fundamental questions about the inner workings of a particle as ubiquitous as the proton. The EIC will, for the first time, precisely image gluons in nucleons and nuclei. It will definitively reveal the origin of the nucleon spin and will explore a new quantum chromodynamics (QCD) frontier of ultra-dense gluon fields, with the potential to discover a new form of gluon matter predicted to be common to all nuclei.

Furthermore, besides the "cold" QCD physics, discovery of novel collective effects in high-energy pp and pA collisions at RHIC and the LHC have raised the question if a hot and dense strongly-coupled quark-gluon liquid is formed there as in large AA collisions, and what is the smallest possible size of a hot QGP droplet [1, 2]. High-luminosity ep/eA collisions at EIC have unique advantages in providing an even smaller system with well-defined initial states and kinematics, and will thus open a new window to investigate "hot" QCD effects in small systems.

1.1 Particle identification at the EIC

Among many promising aspects of EIC physics [3], we are particularly interested in opportunities empowered by excellent particle identification capability over the full phase space. These topics include, but are not limited to:

- Flavor structure of the nucleon via exclusive and semi-inclusive DIS (SIDIS) measurements;
- Heavy flavor meson and baryon reconstruction (also inside jets);
- Search for long-range collective particle correlations in high-multiplicity events.

To extract 3-D flavor-dependent transverse momentum and spacial distributions of partons inside a nucleon, known as the TMD and GPD, separation of pions, kaons, and protons up to tens of GeV in the forward direction is crucial in covering the widest possible (x, Q^2) space. In the cases of heavy flavor hadron reconstruction and search for collectivity, low momentum PID with wide rapidity coverage is particularly important. The flight distance of very low momentum heavy flavor hadrons is too short for a secondary vertex to be resolved so PID provides the most important means to reject combinatorial backgrounds. Long-range collectivity observed in high-multiplicity hadronic collisions spans over at least 10 units in pseudorapidity, and is primarily a low-p_{T} phenomenon (up to a few GeV). Measurements of long-range correlations with identified pions, kaons, and protons provide key discrimination power to different model scenarios (e.g., the mass order of PID spectra and anisotropic flow in hadronic collisions).

1.2 PID requirements at the EIC and the state-of-the-art technology

Two-dimensional momentum (p) and pseudorapidity (η) distributions of pions, kaons, and protons produced in simulated PYTHIA e(18 GeV)+p(275 GeV) collisions are shown in Fig. 1. Distribu-

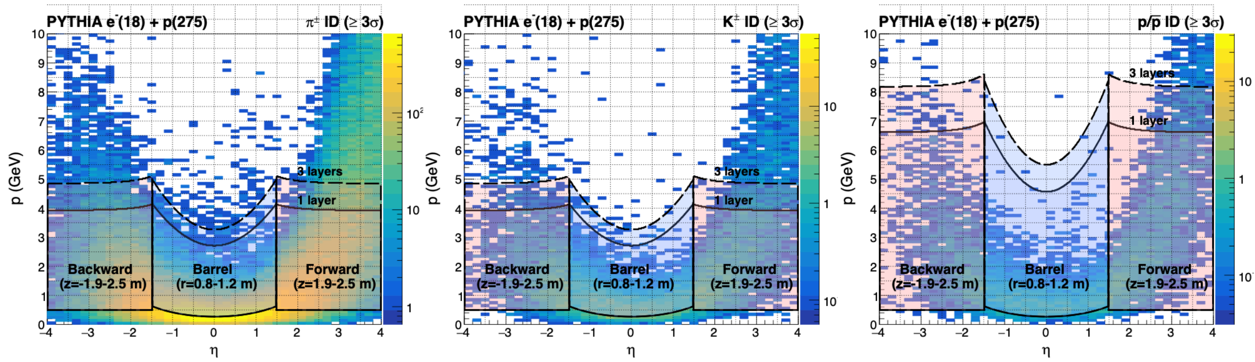


Figure 1: Momentum and pseudorapidity distributions of pions, kaons and protons produced in electron (18 GeV) + proton (275 GeV) collisions from PYTHIA simulations. Shaded areas indicate PID coverage (more than 3σ) by a TOF-tracker system.

tions of particles are highly asymmetric in η with more particles going in the forward direction, spanning well beyond 10 GeV in p. For PID in the region of $p > 10$ GeV, the only viable and well-established technology is the ring imaging Cherenkov counter (RICH). To cover the low momentum region, potential candidates include high-resolution time-of-flight (TOF) sytem (requiring a time resolution of 10–20 ps), DIRC (detection of internally reflected Cherenkov light) or Aerogel RICH (or a combination of them). Pros and cons of various options have been widely discussed (see e.g. a recent summary [4]), which we will not repeat here.

In this proposal, we focus our interests on the low momentum PID, and propose a hermetic TOF system based on a new silicon sensor technology, known as the low gain avalanch diodes (LGAD) [5–7]. The LGADs silicon sensors have a demonstrated time resolution of 30 ps, and are being used to construct a new TOF layer for the CMS and ATLAS experiments at the high-luminosity LHC.

Besides an excellent time resolution, the LGADs also provide high-precision position resolution, and have the unique advantage of being highly compact, a feature that is particularly crucial for an EIC detector with tight space constraints. A multi-layer LGADs system can serve as a dual-purpose detector, not only providing TOF measurements that meets the PID requirement at the EIC but also serving as (part of) a tracker for trajectory reconstruction and momentum determination. A simplified design of a LGAD-based TOF-tracker system, consisting of three layers in the barrel and endcap regions, is shown in Fig. 2. The three layers are placed at $r = 0.8$, 1.0, 1.2 m for the barrel, and $z = 1.9$, 2.2, 2.5 m for the endcap. Assuming a single-layer time resolution of 20 ps (which is the R&D goal as detailed later), the TOF-PID coverage is indicated in Fig. 1 as shaded areas for at least 3σ separation. We consider two possible design scenarios: a single layer as a TOF (solid lines) or three layers as both a TOF and tracker (dashed lines). With a three-layer TOF-tracker sys-

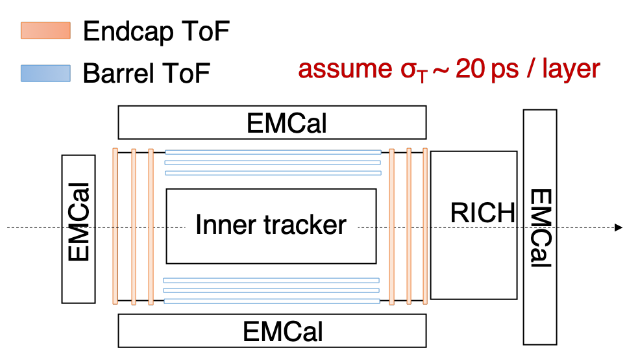


Figure 2: A schematic design of a 3-layer TOF-tracker system based on LGADs.

tem, pions and kaons identification can be achieved up to $p \sim 5$ GeV, while proton identification can extend to $p \sim 9$ GeV over $|\eta| < 4$. Lower limits in momentum reach are largely determined by the tracking capability, magnetic field, and material budgets. Here we assume a magnetic field of 1.5 T. Note that the design in Fig. 2 is only for demonstration purpose and can be further optimized to achieve better performance.

The main goal of this R&D proposal is to

- identify the optimal configuration (thickness and gain) of LGADs that is capable of providing the optimal time resolution of 20 ps or better to meet the TOF-PID requirements at the EIC;
- determine the requirement of position resolution as a tracker and investigate feasibilities of achieving high timing-position resolution with newly developed LGADs technologies.

2 Ultra-fast Silicon Sensor Technology

The Low Gain Avalanche Detector (LGAD) with internal gain [5–10] is an ultra-fast silicon sensor technology, which has recently been chosen for constructing a fast-timing layer in the forward rapidity region of the CMS [11] and ATLAS [12] experiments at the high-luminosity (HL) LHC starting in 2028. The new timing layers will help the experiments mitigate significantly larger pileups of proton-proton interactions (up to about 200) foreseen at the HL-LHC by providing 4-D vertex reconstruction, and also serve as an excellent TOF system for hadron identification in QCD and heavy-ion physics.

In this section, we first introduce basics of the LGAD technology and its state-of-the-art performance in the application of the CMS endcap timing layer (ETL), a project most proponents of this proposal are deeply involved in. Next, we discuss the main limitations of current LGADs used by the LHC experiments, and lay out the proposed R&D path toward solving the issues and identifying a viable option for constructing a hermetic and compact TOF-tracker system at future EIC detectors.

2.1 The Low Gain Avalanche Detectors (LGAD)

The time resolution of silicon detector is largely dominated by the following terms:

$$\sigma_t^2 = \sigma_{jitter}^2 + \sigma_{Landau}^2 + \sigma_{distortion}^2 + \sigma_{TDC}^2 \tag{1}$$

where,

- σ_{jitter}^2: the jitter term is given by the ratio of the noise over the signal slew rate, where the noise is composed of electronic noise and sensor shot noise. The jitter is minimized by large signals, small capacitance, and fast rise time (inversely proportional to the sensor thickness).
- σ_{Landau}^2: the so-called Landau noise arises mainly from signal shape variations due to non-uniform ionization. This is the intrinsic limiting factor for the achievable time resolution. It can be improved by reducing sensor thickness.

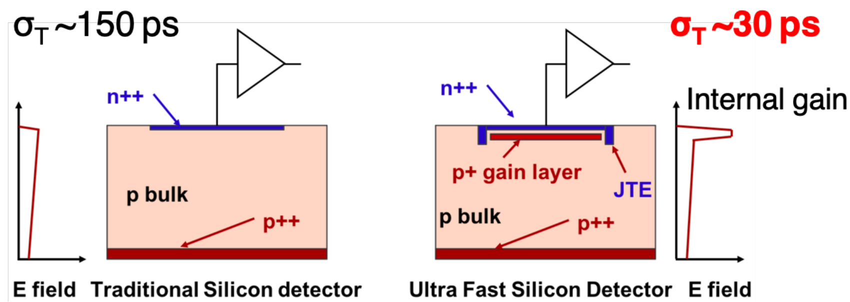


Figure 3: Cross-sectional diagrams comparing a standard silicon detector and a LGAD (or UFSD) with an additional p implant providing the larger electric field needed for charge multiplication.

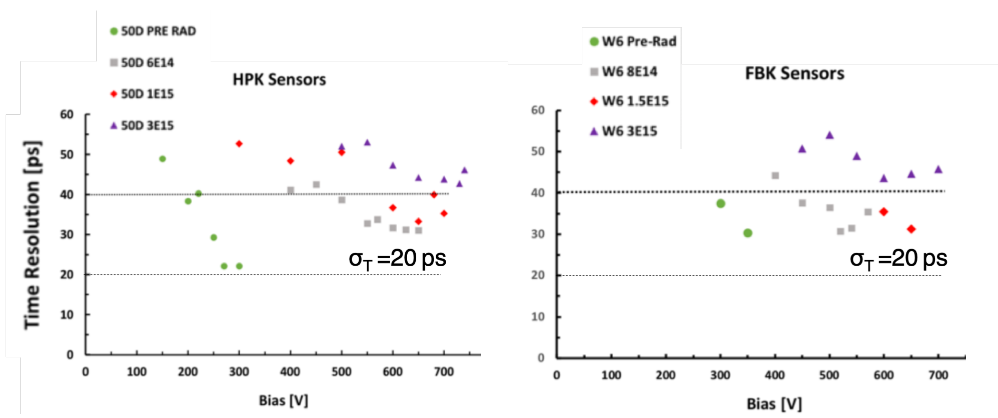


Figure 4: Time resolution measured as a function of bias voltage at different fluences for HPK and FBK LGAD sensors.

- $\sigma^2_{distortion}$: the distortion term is caused by the non-uniformity of weighting field and non-saturated drift velocity. This term can be largely suppressed by using a parallel plate geometry that has a uniform field and operating at a sufficiently high bias voltage to reach saturated drift velocity.

- σ^2_{TDC}: the effect of the TDC binning.

Traditional n-p silicon sensors with gains provided by external bias voltages, illustrated in Fig. 3 (left) can provide a typical time resolution on the order of 150 ps. The LGAD silicon sensors, shown in Fig. 3 (right), have an intrinsic gain of 10–30 provided by a special implant layer to generate a strong electric field locally and trigger avalanches. This internal gain helps the LGADs to achieve a low-jitter fast-rising pulse edge and overcome many other noise sources that enable high precision timing measurements for MIPs. LGAD sensors of 35–50 μm in overall thickness can achieve a typical time resolution of about 30 ps.

Figure 4 shows the time resolution as a function of neutron and proton irradiation for HPK and FBK sensors [11]. These studies are consistent in demonstrating that ultra-fast silicon detectors (UFSDs) maintain a time resolution below 40 ps up to fluences of 1.5 $\times 10^{15}$ neq/cm^2 expected throughout the HL-LHC lifetime. Pre-radiation performance can even reach 20 ps, which is similar to condition foreseen at the EIC.

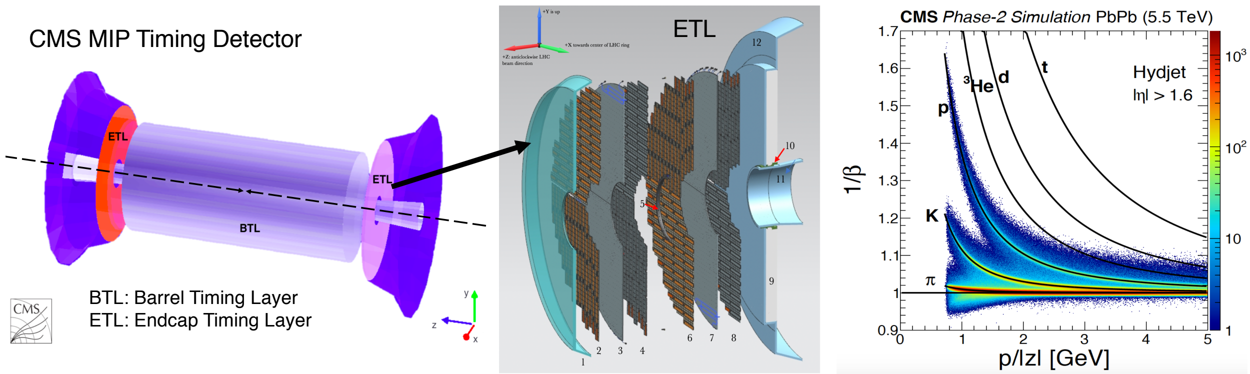


Figure 5: Left: a schematic view of CMS MTD. Middle: design of the two-disk ETL based on the LGADs. Right: TOF-PID performance of $1/\beta$ vs. p in CMS Phase-2 simulations using HYDJET PbPb events.

2.2 The CMS Timing Detector at the HL-LHC

As part of CMS Phase-2 upgrades planned at the HL-LHC, the MIP timing detector (MTD) will provide precision timing measurements with a resolution of 30–50 ps over a hermetic coverage of $|\eta| < 3$. The CMS MTD consists of a barrel (BTL) and an endcap (ETL) timing layer, covering pseudorapidity ranges of $|\eta| < 1.5$ and $1.6 < |\eta| < 3$, respectively, to be installed between the outer tracker and electromagnetic calorimeter. Its cylindrical geometry has a radius of 1.16 m and a half-length of 3 m. A schematic diagram of the MTD is shown in Fig. 5 (left). LYSO crystal scintillators read out with silicon photomultipliers (SiPMs) have been chosen as a mature technology for the BTL, while LGAD silicon sensors have been identified as a viable implementation for the ETL. More details can be found in the Technical Design Report (TDR) [11]. Performance of the MTD as a TOF system for PID has been studied, led by proponents of this proposal, and is shown in Fig. 5 (right).

A cross-sectional view of the CMS ETL design on one side of the interaction region is shown in Fig. 5 (middle). The two-disk ETL system provides a measurement of two hits per track. Each disk has silicon devices on both faces to cover the whole area without cracks or gaps for readout electronics and services. Currently, three vendors are being evaluated as the potential provider of LGAD sensors, including HPK (Japan), FBK (Italy) and CNM (Spain).

Despite demonstrable, excellent performance at the level of a few channels, there are a few other challenges to overcome for constructing a large-scale TOF system consisting of more than 8 million of LGAD readout channels:

- ASIC readout chip is required to have a contribution to the overall time resolution of at most 30 ps, comparable to LGAD sensors, which have never been achieved before.
- The clock distribution system jitter should be no more than 10–15 ps, and negligible to the overall time resolution.
- Radiation hardness of up to a total fluence of 2×10^{15} n_{eq}/cm^2 for the innermost radius. Bias voltages can be independently controlled as a function of radius to maintain the optimal gains over the entire ETL.

- Magnetic field tolerance of up to 4 T.
- Highly compact design with an allowed longitudinal space of 4.5 cm for two disks.

All these challenges are being addressed by ongoing R&D and prototyping efforts, which are expected to conclude by the engineering design review in mid-2022, followed by production, assembly, and final commissioning at the startup of HL-LHC. CMS heavy-ion physics groups (led by KU, MIT, RICE, and UIC) have a major involvement in the ETL project, particularly playing leading roles in the design and construction of service readout electronics and power systems (service hybrids), mechanical structure, as well as R&D, and testing of LGAD sensors and ASIC readout chips. During the production phase, RICE and KU groups will be responsible for QA/QC of service hybrids and LGAD sensors. The HL-LHC will provide the first testing ground of this new technology applied in a large collider experiment. This group aims to leverage the development and experience gained in the ETL project to bring a new and credible detector option to the EIC program.

2.3 Limitations and R&D path toward a TOF-tracker system at the EIC

The LGADs provide an attractive option for constructing a compact, multi-layer system to simultaneously provide trajectory reconstruction and particle identification. One big advantage at the EIC is the much lower radiation level ($\sim 10^{11}$ n_{eq}/cm^2) compared to the HL-LHC ($\sim 2 \times 10^{15}$ n_{eq}/cm^2 for ETL). Therefore, radiation hardness of the detector is not a major concern. To fulfill the requirements for EIC physics, however, there are two limitations of the present LGADs that require improvements:

- Time resolution: while LGAD silicon sensors used by CMS and ATLAS can provide a time resolution of 30–50 ps, particle flight distance at EIC detectors is likely to be much shorter due to tight space constraints. Therefore, a time resolution of 20 ps or better is desired to meet the PID requirement at low momentum regions.
- Fill factor and position resolution: to serve as (part of) a tracker, a position resolution much better than the 1 mm pixel size has to be accomplish to be competitive to other types of silicon pixel and/or strip sensors that are designated for position measurements. The current limitation lies in the approximately 50 μm width of the intra-pad no-gain region, which is needed to protect against early breakdowns. Smaller pixel sizes would lead to too low fill factors, or loss of acceptance. The CMS ETL has a fill factor of 85% per disk, with the two-disk system compensating for a 100% acceptance.

Owing to rapid developments of the LGAD technology in recent years, potential solutions to limitations mentioned above already exist. An R&D program targeted specifically on meeting requirements of EIC detectors will address both limitations, as detailed below and illustrated in Fig. 6:

- The jitter contribution to the time resolution is directly related to the signal slew rate, which is inversely proportional to the sensor thickness (illustrated in Fig. 6, left). Reducing the

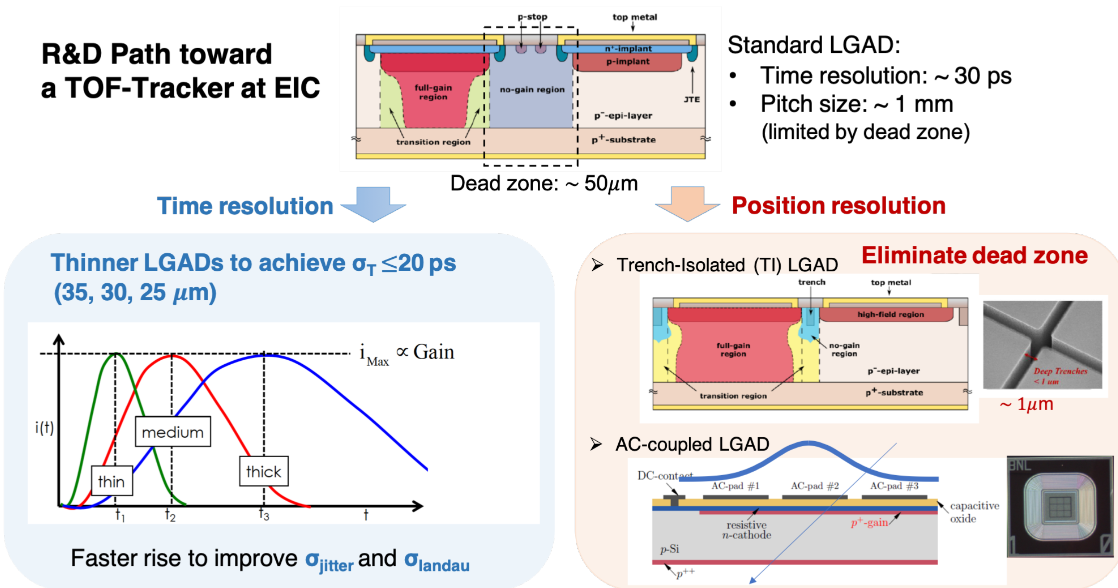


Figure 6: Summary of the R&D path toward realizing a TOF-tracker at EIC using LGADs.

thickness from 50 μm to 35, 30, and even 25 μm will not only improve the jitter but can also suppress the Landau noise. Note that the total charge collection will also be reduced proportionally, leading to a smaller signal. Gain layers with a higher doping concentration may be needed to compensate for it.

Thinner LGADs are not applicable for the HL-LHC due to faster degradation of performance (i.e., sufficiently large gains are difficult to maintain) after irradiation. As radiation hardness is not a main concern at EIC, we can focus the R&D on identifying the optimal thickness and gain scheme of LGADs that provide the best time resolution.

- To achieve better position resolution (beyond 1 mm pixel size), two viable solutions are present, illustrated in Fig. 6 (right). Trench-isolated (TI) LGADs is capable of reducing the no-gain region down to a width of only a few μm, essentially eliminating it to achieve 100% fill factor. All readout schemes can be kept the same as standard LGADs. For AC-coupled LGADs, segmentation is not done on the silicon sensor but at metallic readout contacts sitting on top of a dielectric layer, reading out induced charges. The fill factor is effectively 100%. The signal pulse is shared among several adjacent pads, further improving its position sensitivity. The metallic readout pads can be fabricated into pixels, strips or any shape desired. BNL is among leading developers of AC-LGADs (others include FBK and CNM).

3 Proposed Work and Deliverables

In this one-year R&D program, we will address the most pressing issues as outlined in Section 2.3 and Fig. 6. In this section, we discuss our proposed work in three parts, including deliverables and a timeline.

The team is highly experienced in fast-timing silicon technology. Besides the MTD and CT-

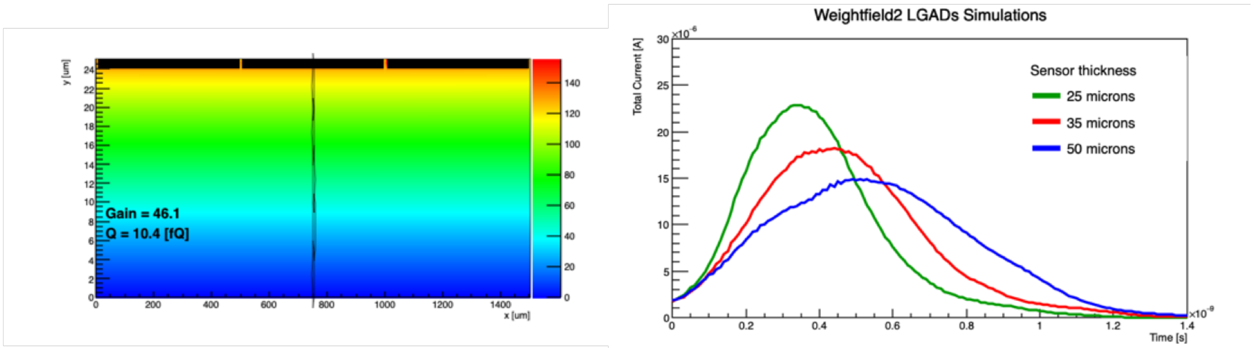


Figure 7: Weightfield2 LGADs simulations: example of potentials and gain in a 25 μm sensor (left) and comparison of currents from 25, 35, 50 μm sensors with a total charge collection of about 10 pC (right).

PPS projects at the CMS experiment, Prof. C. Royon is also leading KU's side of the NASA AGILE project to construct a cosmic-ray telescope detector in space based on the LGADs. Full teststands with infrared-laser based TCT and β-sources are available at RICE and KU, where the work on sensor characterization will be primarily carried out. ORNL has a strong nuclear physics group on the ALICE and (s)PHENIX experiments, with strong expertise in developing readout chips and boards. Additionally, the RICE group has lead the R&D, design, and construction of STAR's TOF systems, including its electronics. It is worth mentioning that we have been generously offered help from our CMS collaborators at INFN Torino and FNAL which includes technical support and consultants, use of testing facilities, and the procurement of specific LGAD sensors as needed. Opportunities of beam tests may be available at FNAL as part of the CMS ETL program. Meanwhile, by collaborating with BNL groups in the physics and instrumentation departments, we will also make use of the testing and silicon fabrication facility there, especially for new sensor productions.

3.1 Part I: R&D of ultra-thin LGAD sensors (10/2020–03/2021)

Our first step will focus on establishing the best possible time resolution (20 ps or better) via a systematic characterization of the thinner LGAD sensors. We have performed simulations with WeightField2 to predict signal currents of LGADs with thicknesses of 50, 35, and 25 μm, as shown in Figure 7. For each thickness option, the bias voltage is chosen to provide a gain that generates a total charge collection of about 10 pC, which is the minimum amount of charge required for a quality timing measurement. Signals of thinner sensors have faster slew rates and a higher peak values for fixed total charge collection, which is expected to provide a better timing performance.

We will carry out measurements to verify the simulation results in Fig. 7. Sample sensors of 50 μm (chosen by CMS and ATLAS) and 35 μm in thickness are available from HPK, FBK, and CNM. Standard LGADs with 55, 45, and 25 μm thickness will also be available from FBK soon. Our CMS collaborator, Nicolo Cartiglia (INFN Torino), will kindly help us acquire a set of sample sensors with desired configurations.

Sensor characteristics and performance (e.g. gains, time resolution) for each thickness option will be studied and compared using infrared laser TCT and β sources. An MCP-PMT will be used as a trigger reference detector with a typical time resolution of 10–15 ps. Signals will be extracted by mounting sample sensors onto a UC Santa Cruz readout board for further analyses. We also plan to test sensor performance under different temperature conditions. A schematic of our teststand is shown in Fig. 8. If opportunities of beam tests at FNAL become available (for CMS ETL, possibly early next year), we will seek to join the program so that more detailed characterization of thinner LGADs can be obtained using high-energy particles.

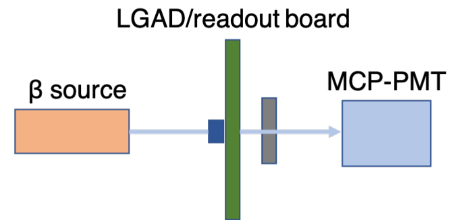


Figure 8: A schematic of teststand for LGADs characterization.

This part of the work will be carried out by a postdoc at RICE and an undergraduate researcher at KU. Once the LGAD configuration for the desired time resolution is determined, we plan to collaborate with the BNL group to fabricate such sensors at BNL and verify their performance again. The ASIC readout chip is also a crucial element and it should match the timing performance of the LGADs. We have decided to leave the chip design outside the scope of this one-year program but will follow up in the future. Our strategy would be to leverage the latest developments of ETROC at CMS and ALTIROC at ATLAS to understand specific limitations there and have a targeted R&D effort on ASIC chips in future projects.

Deliverables of Part I from 10/2020 to 03/2021 are summarized below:

- Detailed characterization of standard LGADs for a variety of sensor thicknesses using lasers, β sources, and (if possible) proton beams at FNAL to determine the LGADs configuration optimized for the best time resolution without irradiation.

3.2 Part II: simulations of a LGAD-based TOF-tracker (10/2020–05/2021)

In parallel with work of optimizing LGADs timing resolution in Part I, we will proceed with simulations studies to fully evaluate the required position resolution of LGADs for a tracker. This includes evaluating the impact of material budgets, its optimal location and layout, and benefits of precision timing information to track momentum and back-pointing resolutions. This part of the work has a strong synergy with the EIC tracker/tracking group, which we will capitalize on to strengthen the collaboration and avoid duplication of work.

Proposed simulation work will be led by a postdoc at ORNL and one graduate student from RICE. We will carry out the work within the simulation framework established by the EIC software consortium and implement the LGADs layers with a layout sketched in Fig. 2: first in fast simulations with `eic-smear` library, and then in full simulations with `Fun4All`. We will primarily investigate the option of placing LGADs layers in the outermost region of the tracker to benefit from long flight distances for PID. For the inner tracker, we will make use of existing implementations such as MAPS-based silicon pixel detectors.

Deliverables of Part II from 10/2020 to 05/2021 are summarized below:

- Realistic TOF-PID performance, including effects of start-time (t_0) determination, based on

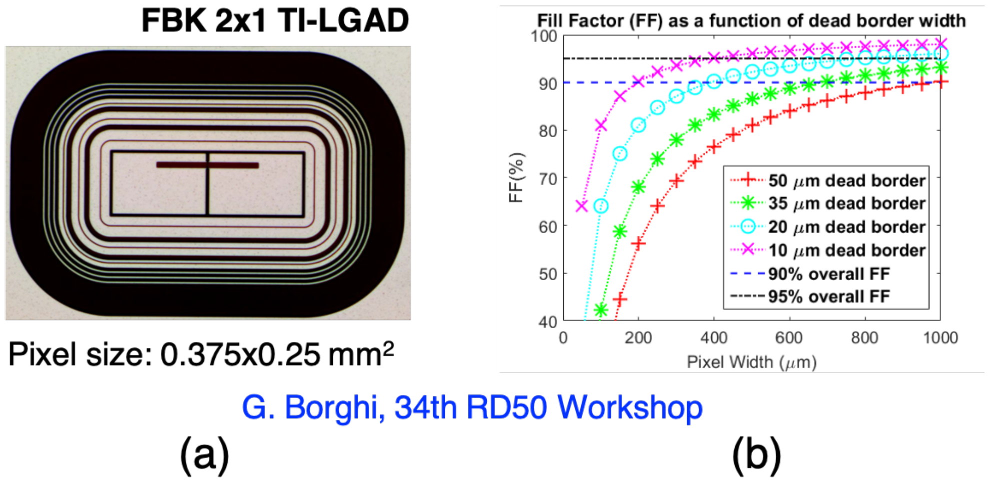


Figure 9: (a) a 2×1 TI-LGAD sensor fabricated by FBK; (b) simulations of fill factors as a function of pixel width for different width of no-gain region [13].

sensor time resolution achievable from work in Part I.

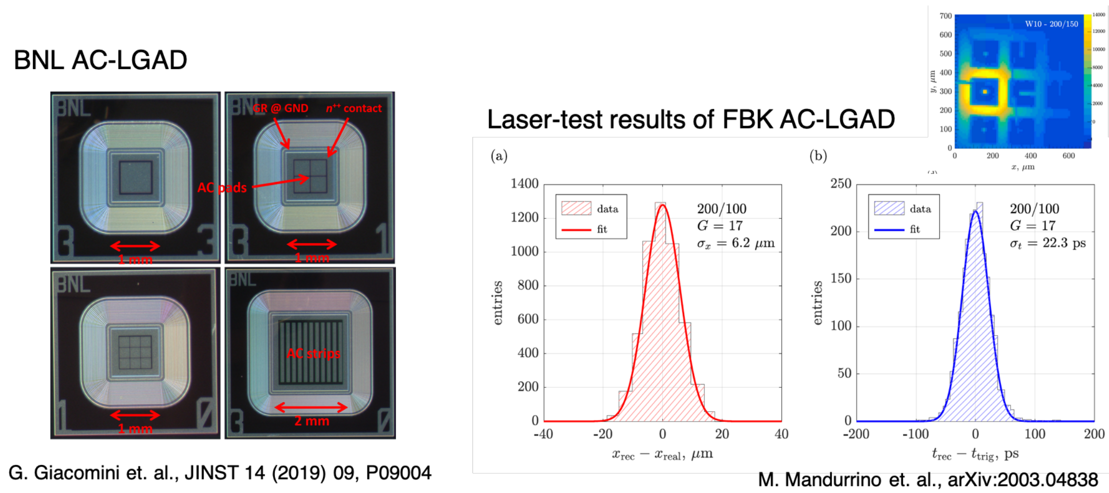
- Determination of LGADs pitch sizes needed to achieve the required track momentum and back-pointing resolutions at EIC.
- Studies of benefits from combined position and timing information to tracking.

3.3 Part III: R&D of AC-coupled and TI-LGAD sensors (03/2021–09/2021)

With work in Part I and II accomplished, we arrive at the final step of this project to realize LGAD sensors with both high timing and position resolution for a TOF-tracker system at the EIC. This part of the work will be carried out by the same workforce mentioned in Part I. As introduced in Section 2.3, LGADs currently used by the CMS and ATLAS experiments have a pitch size of ~ 1 mm, limited by the intra-pad no-gain region. This is likely insufficient precision for a tracker but possible solutions already exist.

The LGADs with trench isolation (TI-LGAD) have been fabricated by FBK for 50 μm thickness [13]. Figure 9 (left) shows the image of a sample TI-LGADs with 2×1 pixels and a pixel size of $375 \times 250\,\mu\mathrm{m}^2$. The no-gain region is reduced to the order of a few microns. Figure 9 shows how the fill factor depends on the pixel width and size of non-gain region. With the TI-LGADs, a fill factor of more than 90% for a pixel width of 100–200 μm is within the reach.

With our setups in Part I, we will test sample TI-LGADs sensors and perform a direct comparison with standard LGADs sensors with the same thickness. If performance in terms of time resolution is comparable, we will seek for the possibility of producing TI-LGADs by FBK with thickness determined from Part I and pitch size determined from simulations in Part II. We should note that new sensor production may be time-consuming and require coordination with vendor's schedule so we cannot fully guarantee this to be done within this one-year project. Nevertheless,



(a) (b)

Figure 10: (a) AC-LGADs in pixels and strips fabricated by BNL [14]; (b) test results of FBK AC-LGADs by lasers on timing and position resolutions [15].

it is promising to pursue this possibility even for a little longer term. It will be a vital contribution to the development of LGADs technology in general.

Another solution to reach high precision in position is the AC-coupled LGADs. As mentioned earlier, BNL is a world-leading developer in AC-LGAD technology. Sensors developed and fabricated by the BNL group are shown in Fig. 10 (left), including both pixel and strip configurations with a smallest pitch size of $\sim 200\,\mu$m [14]. The AC-LGADs of $55\,\mu$m thick are also fabricated by FBK. Figure 10 (right) shows recent testing results of FBK AC-LGADs sensors using infrared lasers [15]. A time resolution of about 22 ps is achieved. More impressively, a position resolution of a few μm is achieved with a pitch size of 200 μm, thanks to the signal sharing among multiple readout pads.

Currently, the BNL group is developing the AC-LGAD technology for constructing high position and timing resolution Roman Pots under the BNL EIC R&D program. We will establish a strong collaboration to leverage the synergy between the two projects. In particular, the BNL instrumentation group has the capability of fabricating AC-coupled LGADs with specifications (thickness, granularity) determined from this proposal for a TOF-tracker system.

Deliverables of Part III from 03/2021 to 09/2021 are summarized below:

- Studies of the performance of the FBK TI-LGAD and direct comparisons to standard LGAD at the same thickness (50 μm). If comparable performance in time resolution without irradiation is demonstrated, seek for production of thinner TI-LGADs (if possible and time allows) with desired pixel sizes determined by simulations in Part II.

- Fabrication of AC-coupled LGADs with desired thickness and pixel sizes in collaboration with the BNL group.

4 Proposed Budget and Labor

4.1 Budget justification

Labor

We propose 0.6 FTE ($54k) support of a current RICE postdoc, Shuai Yang, and partial support ($3k) of an undergraduate researcher at KU, William Doumerg, by the EIC detector R&D program and lead most of the proposed detector work defined in Parts I and III. RICE postdoc, Shuai Yang, is an expert on photonuclear interactions and a key member of the RICE team on ETL. He has performed simulations for heavy-ion physics cases and is working on testings of ETL prototype readout boards.

M&S

We will leverage as much as possible existing resources, lab facilities and personnel at each institute, especially those from the CMS ETL and NASA AGILE projects so only a small amount of M&S funds ($5k) is requested mainly for acquiring and producing LGAD sensors.

Travel

Given the uncertainty of COVID-19 pandemics, we request very limited travel funds ($1k) for ORNL to make one domestic trip to RICE and collaborate on the simulation work for a period of time. We will use external resources for additional travels if allowed and needed.

4.2 Budget summary including reduced scenarios

Budget breakdowns by costed items and by institutions are summarized in Tables 1 and 2, respectively.

As per the guideline, we also include scenarios of reduced total budget by 20% and 40%, respectively.

- In 20% reduced scenario, we will drop any new fabrication of LGADs, or seek for other resources. With reduced postdoc FTEs, we will focus on studying only AC-coupled LGADs (dropping TI-LGAD) in collaboration with the BNL group for Part III.
- In 40% reduced scenario, it would only be possible to pursue the Part I of this proposal to focus on optimizing the timing performance.

4.3 Contributed resources

One graduate student from RICE and 0.5 FTE of one postdoc from ORNL (a new position is being filled on sPHENIX and EIC) will lead the simulation work and assist in the proposed detector

Table 1: Budget breakdown by costed items, including reduced scenarios by 20% and 40%.

Costed Item	100%	80%	60%
Labor	$57k	$48k	$36k
M&S	$5k	$2k	$2k
Travel	$1k	$1k	0
Total	$63k	$51k	$38k

Table 2: Budget breakdown by institutions, including reduced scenarios by 20% and 40%.

Institute	100%	80%	60%
RICE	$59k	$47k	$38k
KU	$3k	$3k	0
ORNL	$1k	$1k	0
Total	$63k	$51k	$38k

activities as contributed resources. At KU, Alexander Novikov (post-doc), Tommaso Isidori, and Florian Gautier (graduate student), who are working on the NASA project, can provide assistance to this project.

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